

Gas Flow Measurement - Practical Work

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SUMMARY

This paper shows the basic equations for gas flow measurement. Furthermore, the principles of gas flow measurement by the Prandtl tube as well as the Orifices and Nozzles are explained.

Some of the presented principles and instruments will be used for the practical work carried out on a test equipment in the laboratory hall.

1. THEORETICAL BASIS

1.1 The Law of Bernoulli

(Daniel Bernoulli, 1700..1782 Swiss Scientist)

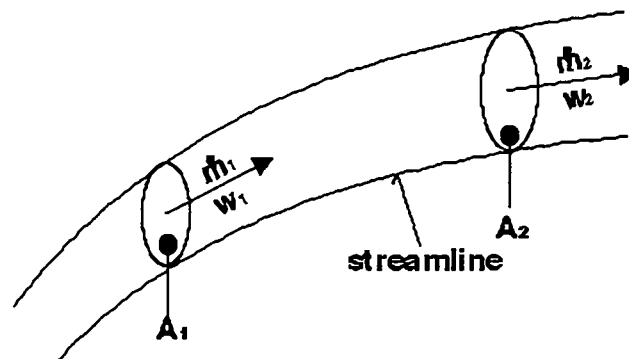
In aeronautics, a law or theorem state that in a flow of incompressible fluid the sum of the static pressure and the dynamic pressure along a streamline is constant if gravity and frictional effects are disregarded.

Resultant from this law is that if there is a velocity increase in a fluid flow, there must be a corresponding pressure decrease. Thus an airfoil, by increasing the velocity of the flow over its upper surface, drives lift from the decreased pressure.

As originally formulated, a statement of the energy conservation (per unit mass) for a non-viscous fluid in steady motion. The specific energy is composed of the kinetic energy $v^2/2$, where v is the speed of the fluid; the potential energy gz , where g is the acceleration of gravity and z is the height above an arbitrary reference level; and the work done by the pressure forces of a compressible fluid $\int v dp$, where p is the pressure, v is the specific volume, and the integration is always with respect to value of p and v on the same parcel. Thus, the relationship

$$v^2/2 + gz + \int v dp = \text{constant along a streamline}$$

is valid for a compressible fluid in steady motion, since the streamline is also in path. If the motion is irrational, the same constant holds for the entire fluid.



If the fluid is compressible

$$\dot{m}_1 = \dot{m}_2$$

$$\rho_1 \cdot \dot{V}_1 = \rho_2 \cdot \dot{V}_2$$

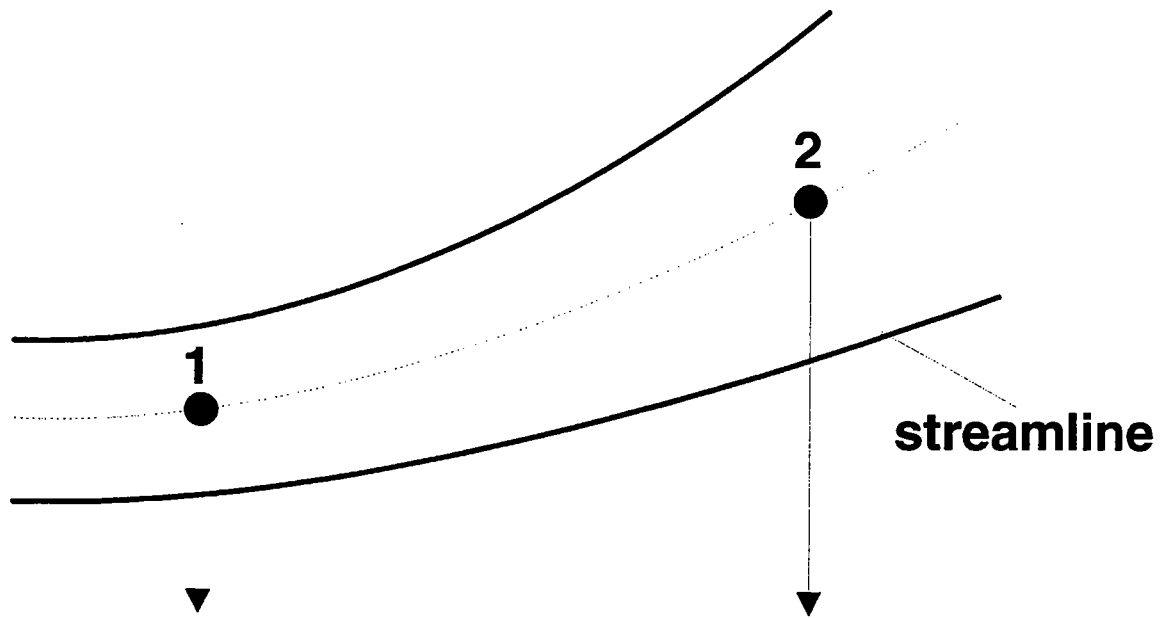
$$\rho_1 \cdot A_1 \cdot w_1 = \rho_2 \cdot A_2 \cdot w_2$$

If the fluid is incompressible:

$$\rho_1 = \rho_2$$

$$\dot{V}_1 = \dot{V}_2$$

$$A_1 \cdot w_1 = A_2 \cdot w_2$$



Sum of energies in point 1 = Sum of energies in point 2

$$\frac{P_1}{\rho_1} + \frac{w_1^2}{2} = \frac{P_2}{\rho_2} + \frac{w_2^2}{2}$$

If the fluid is incompressible, that means ρ is constant:

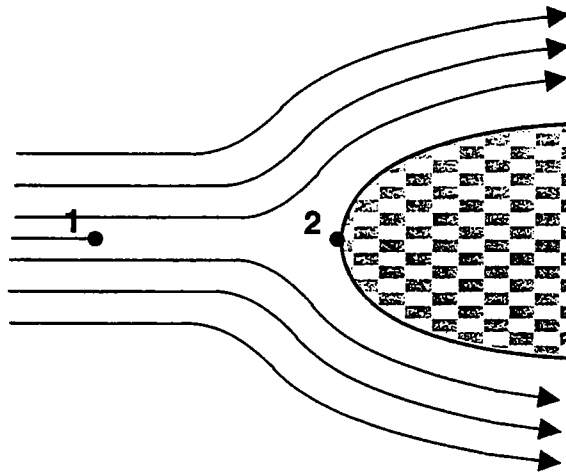
$$\rho_1 = \rho_2 = \rho$$

$$\frac{P_1}{\rho} + \frac{w_1^2}{2} = \frac{P_2}{\rho} + \frac{w_2^2}{2}$$

Symbols and units:

| | | |
|-----------|--|------------------------|
| A | Cross section area | [m ²] |
| d | Diameter of the smallest aperture | [m] |
| D | Diameter of the tube | [m] |
| m | Cross section area ratio $m = d^2 / D^2$ | [-] |
| \dot{m} | Mass flow rate | [kg/s] |
| p | Pressure | N / m ² |
| ∇ | Volume flow rate | [m ³ / s] |
| w | Velocity | [m / s] |
| ρ | Density | [kg / m ³] |

2. LOCAL VELOCITY AND PRESSURE MEASUREMENTS



The above figure shows a fluid flowing around an obstacle. One of the streamlines reaches the body at the point 2, called stagnation point. At this point the velocity of the fluid is zero.

The Bernoulli equation, for the undisturbed flow at point 1 to point 2,

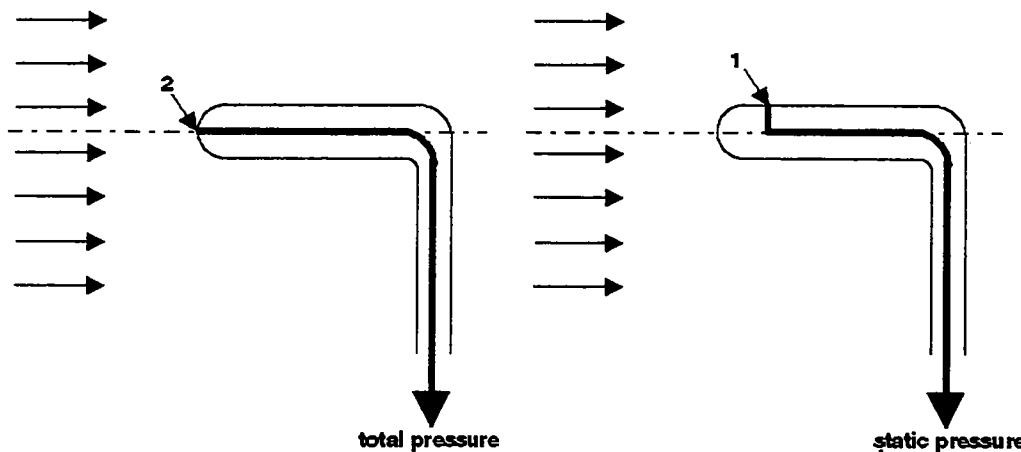
$$\frac{P_1}{\rho} + \frac{w_1^2}{2} = \frac{P_2}{\rho} + \frac{w_2^2}{2} \quad \text{or } (w_2 = 0) \quad P_2 = P_1 + \frac{\rho}{2} w_1^2$$

where P_2 is the total pressure
 P_1 is the static pressure
 $\frac{\rho}{2} w_1^2$ is the dynamic pressure

p_2 , p_1 and $\frac{\rho}{2} w^2$ are pressures called total, static and dynamic pressure.

2.1 The Measurement of the Pressures

The total pressure of a fluid can be measured at a stagnation point. For this purpose the so-called Pitot tube is used.



At the point 2 a stagnation point is created where the **total pressure** can be measured.

A boring placed vertically to the flow (1) measures the pressure independent from the direction. This pressure is called **static pressure**.

3. GAS FLOW MEASUREMENT BY THE PRANDTL TUBE

The dynamic pressure, defined as

$$\frac{\rho}{2} \cdot w_1^2$$

can be expressed as the pressure difference between the total and the static pressure. The relation is

$$p_2 - p_1 = \frac{\rho}{2} w_1^2$$

This difference is measured with the Prandtl Tube.

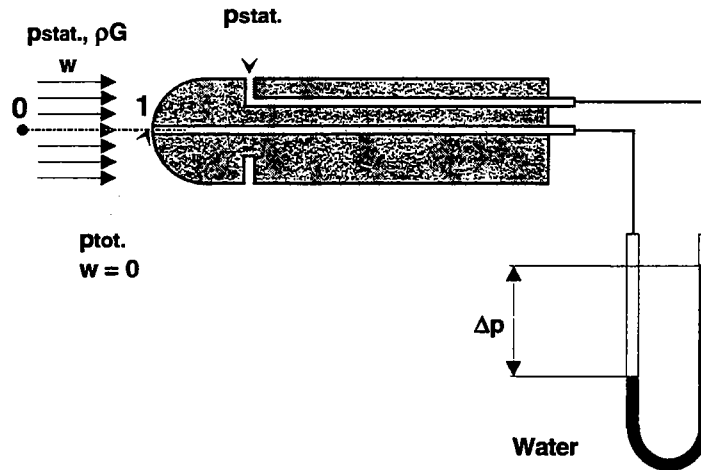


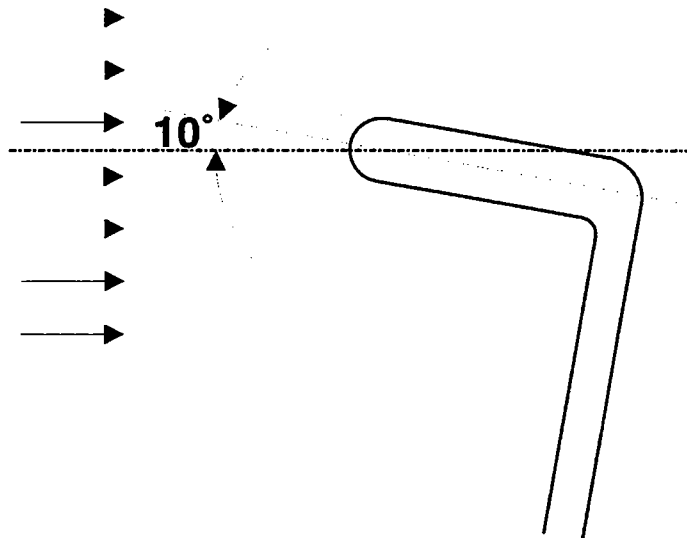
Fig.2

The inner part of this instrument corresponds exactly to a Pitot Tube and the total pressure is measured there. The outer part has the function of the static pressure measurement.

The difference between the two connections is the dynamic pressure.

The direction of the flow should correspond to the axis of the Prandtl Tube. Deviations until $\pm 10^\circ$ however, do not essentially influence the measuring accuracy.

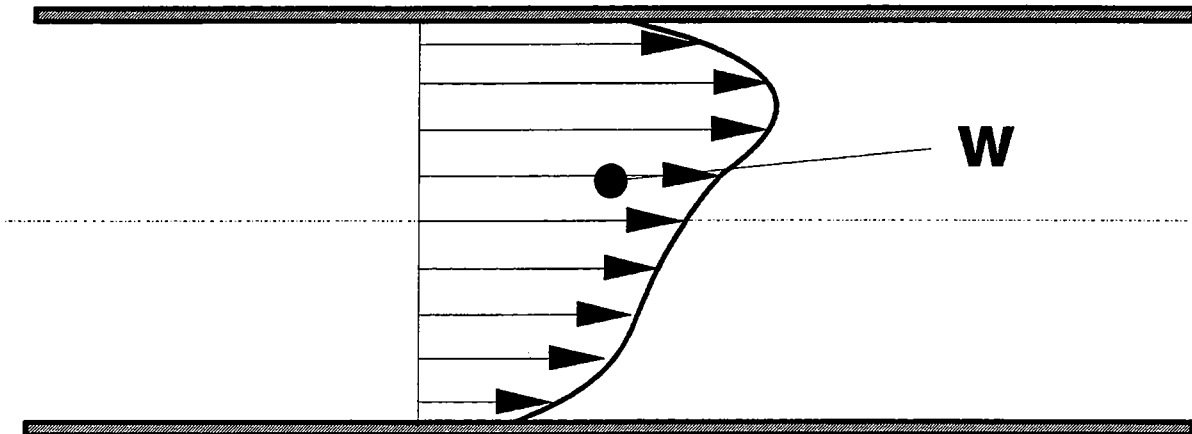
The error in the measurement of the pressure is below $\pm 1\%$.



With the dynamic pressure the fluid velocity can be calculated as follows:

$$w_1 = \sqrt{\frac{2 \cdot (P_2 - P_1)}{\rho}}$$

The Prandtl Tube measures a local velocity only. In order to get an integral velocity (e.g. the average value) the integration of several local velocities over the cross sectional area must be made.



$$w = \frac{1}{A} \iint_A w \cdot dA$$

The gas flow rate is finally calculated by multiplying the average gas velocity with the cross sectional area.

Specific information on the gas flow measurement by the Prandtl Tube is given in chapter 6 "Practical work in gas flow measurement".

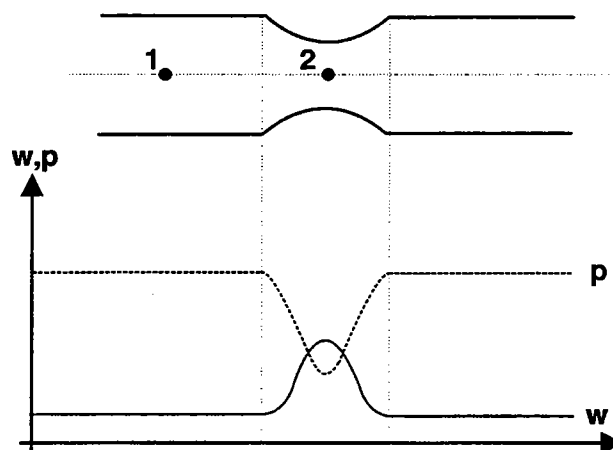
4. INTEGRAL GAS FLOW MEASUREMENT WITH NOZZLES AND ORIFICES

The idea of this method is to create a change of cross section of the whole fluid stream. By means of this change also the pressure and the velocity change and from the pressure difference the velocity can be calculated.

A precondition for this measurement method is a more or less equalized velocity profile. Disturbances like

- ◆ Flow separation behind bends, valves, etc.
- ◆ Pulsation behind a piston type compressor
- ◆ High dust loading
- ◆ etc.

falsify the measurement and make it useless in a lot of cases. As a rule of thumb it can be said that prior to such a flow measurement a straight tube length of more than 10 tube diameters is to be provided.



Between point 1 and 2 the continuity condition can be formulated as

$$A_1 \cdot w_1 = A_2 \cdot w_2$$

Between the same two points the Bernoulli equation (see 1.1) gives:

$$\frac{p_1}{\rho} + \frac{w_1^2}{2} = \frac{p_2}{\rho} + \frac{w_2^2}{2}$$

From the two relations the following equation is derived:

$$w_1 = \frac{\sqrt{2 \cdot (P_1 - P_2)}}{\sqrt{\rho \cdot \left[\left(\frac{A_1}{A_2} \right)^2 - 1 \right]}}$$

The velocity w_1 can be calculated from the pressure difference between the undisturbed flow (point 1) and the accelerated flow in the smallest cross-sectional area.

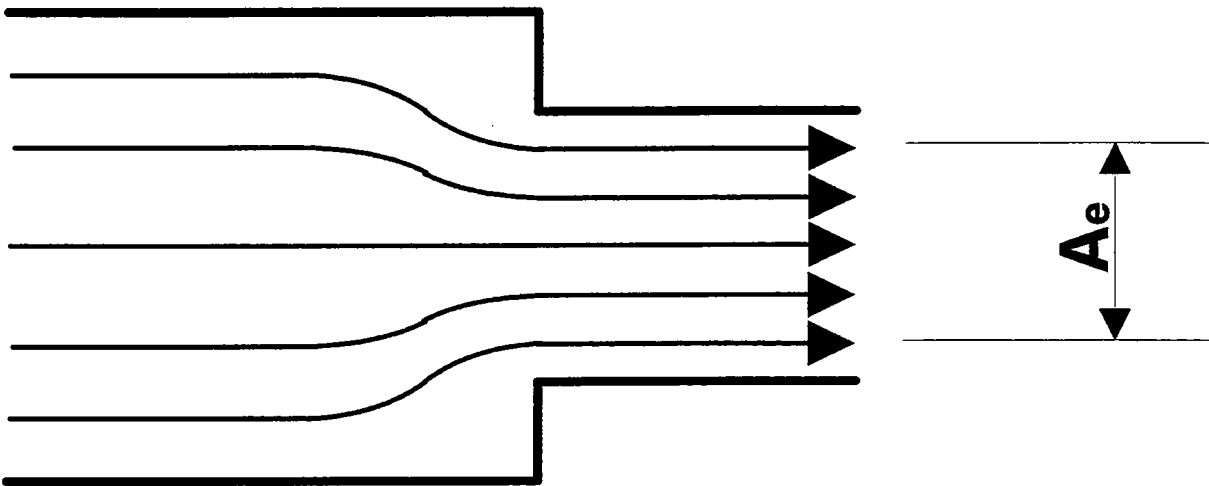
The pressure p_2 is lower than pressure p_1 and compared to the pressure p_1 , is p_2 a negative pressure.

The relation is

$$(P_1 - P_2) = \frac{\rho}{2} W_1^2 \left[\left(\frac{A_1}{A_2} \right)^2 - 1 \right]$$

The pressure difference is a function of the ratio square of the cross sectional area. Great ratios produce therefore extreme underpressures! An example of such a great ratio is the reduction of the cross-sectional area during coating formation in preheaters.

The change of the cross-section causes, especially when it is done suddenly, a disturbance of the flow. The fluid cannot follow the wall and a contraction of the stream is produced.

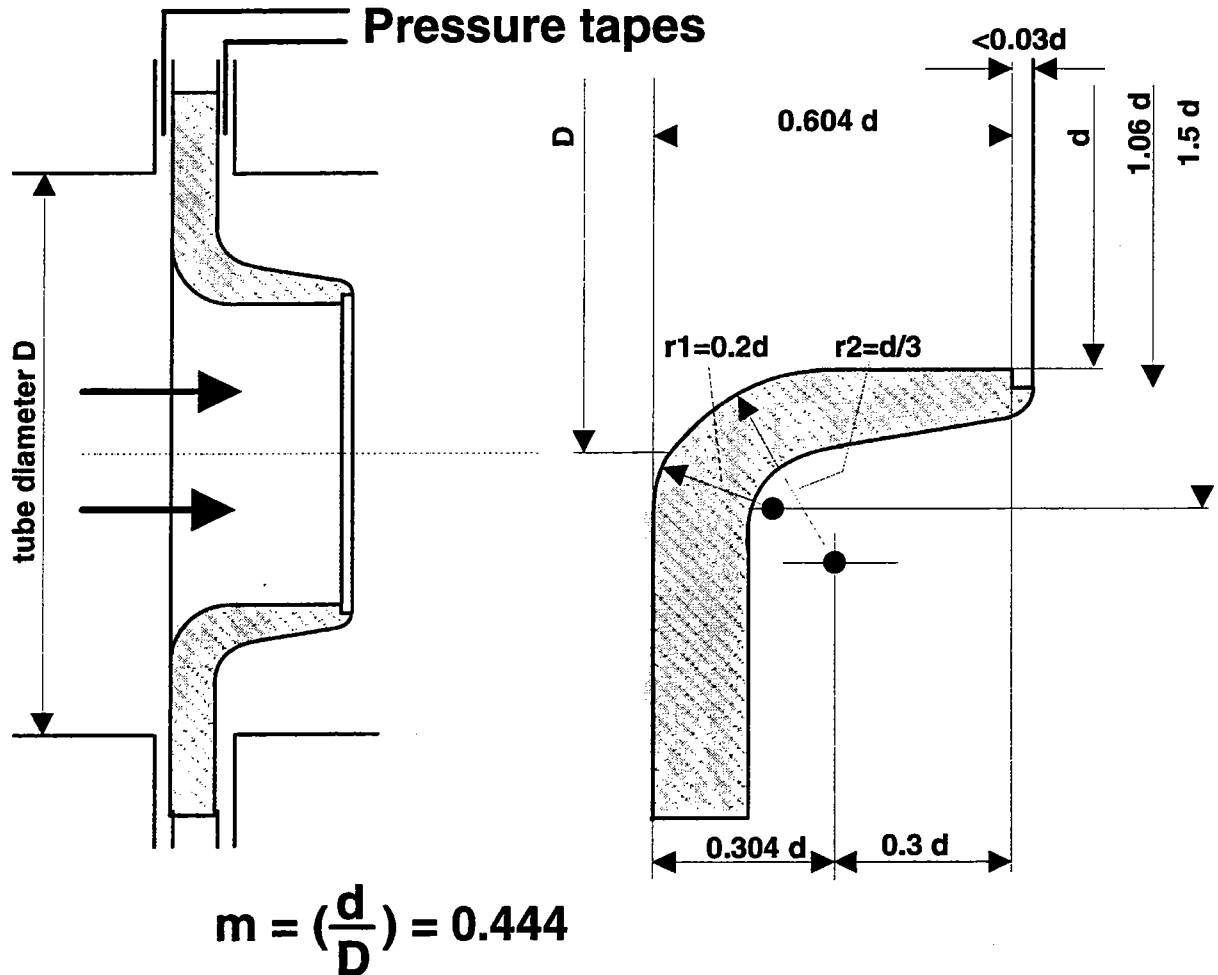


The effective cross section A_e is now smaller than the real one and the calculated velocity must be corrected. The correction cannot be calculated, it must be measured. For this reason several types of integral measuring instruments are standardized by DIN 1952.

In the following the 3 basic standard instruments are sketched:

4.1 Standard Nozzles

Standard nozzles are used for tubes with diameters from 50 to 500 mm and a cross-sectional ratio (smallest area against tube area) of 0.1 to 0.64.



The velocity in the tube and the volume flow, respectively, are calculated by the following relation:

$$w = \alpha \cdot \varepsilon \cdot m \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho_1}}$$

$$\dot{V} = \alpha \cdot \varepsilon \cdot m \cdot \frac{\pi}{4} \cdot D^2 \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho_1}}$$

The factor ε considers the change in the density of a compressible fluid. For incompressible fluids (e.g. water or air until a maximum velocity of 100 [m/s]) this factor has the value 1, otherwise it is tabulated in the DIN - Standards 1952.

The value α is the correction factor for the contraction of the fluid. It is a function of the Reynold's number and the ratio m of the cross-sectional areas. This factor is also tabulated in the DIN - Standards 1952. The table below shows an output of these standards.

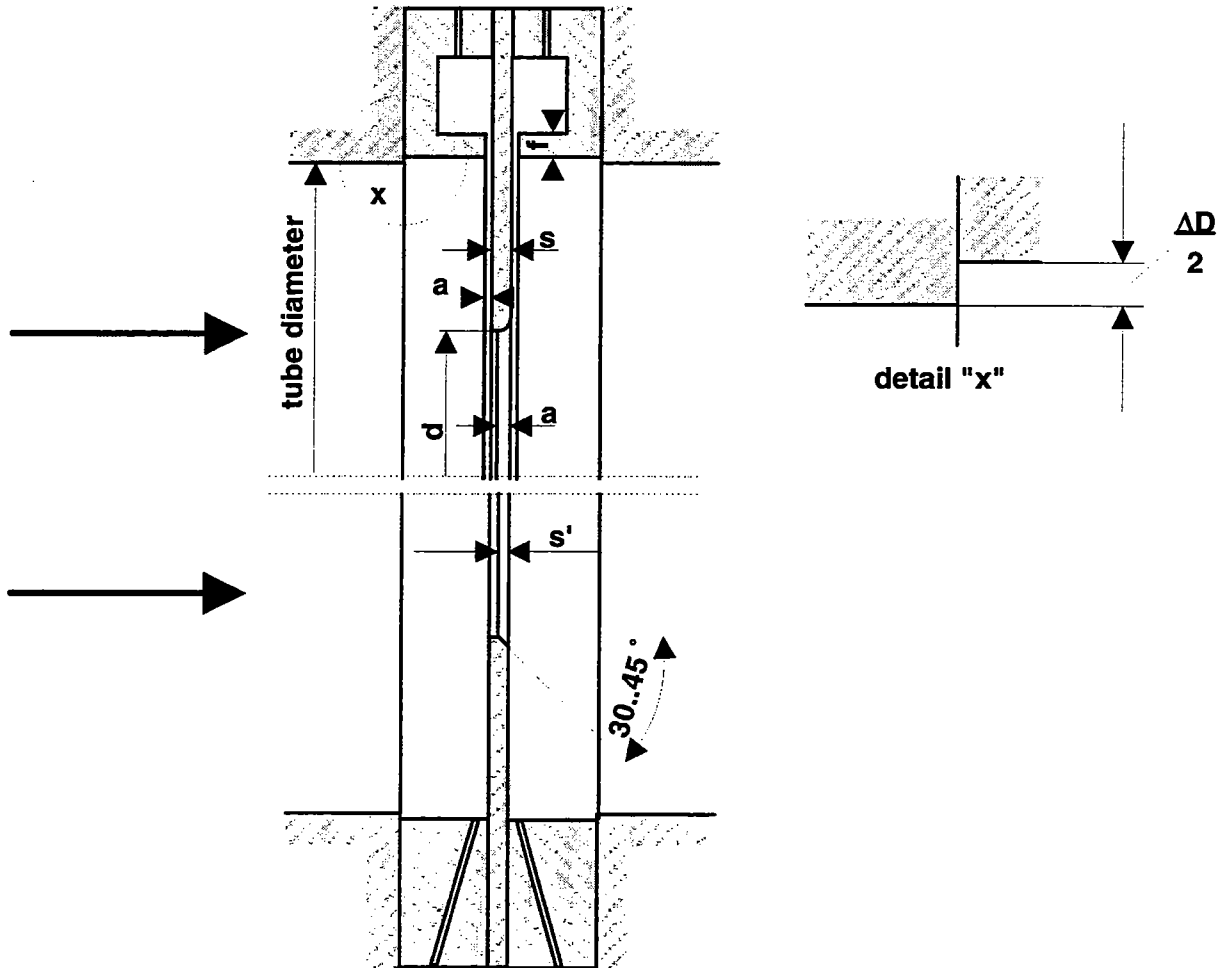
Correction factors for the contraction $\alpha = f(m^2, Re)$ for standard nozzles in tubes with smooth surfaces, valid for diameters D between 50 and 500 mm. Between the indicated values of m^2 (not m) can be interpolated linearly.

| Re | | 2 · 10 ⁴ | 2,5 · 10 ⁴ | 3 · 10 ⁴ | 4 · 10 ⁴ | 5 · 10 ⁴ | 7 · 10 ⁴ | 10 ⁵ | 2 · 10 ⁵ | 10 ⁶ bis 2 · 10 ⁶ |
|--------|----------------|---------------------|-----------------------|---------------------|---------------------|---------------------|---------------------|-----------------|---------------------|---|
| m | m ² | α | | | | | | | | |
| 0,1000 | 0,01 | | | | | | 0,9892 | 0,9895 | 0,9895 | 0,9896 |
| 0,1414 | 0,02 | | | | | | 0,9917 | 0,9924 | 0,9927 | 0,9928 |
| 0,1732 | 0,03 | | | | | | 0,9945 | 0,9954 | 0,9959 | 0,9960 |
| 0,2000 | 0,04 | 0,9978 | 0,9849 | 0,9883 | 0,9926 | 0,9951 | 0,9973 | 0,9984 | 0,9992 | 0,9994 |
| 0,2236 | 0,05 | 0,9822 | 0,9871 | 0,9906 | 0,9951 | 0,9977 | 1,0002 | 1,0015 | 1,0026 | 1,0027 |
| 0,2449 | 0,06 | 0,9849 | 0,9895 | 0,9930 | 0,9976 | 1,0005 | 1,0033 | 1,0047 | 1,0059 | 1,0061 |
| 0,2646 | 0,07 | 0,9876 | 0,9921 | 0,9956 | 1,0002 | 1,0033 | 1,0064 | 1,0080 | 1,0093 | 1,0095 |
| 0,2828 | 0,08 | 0,9907 | 0,9951 | 0,9984 | 1,0031 | 1,0063 | 1,0096 | 1,0113 | 1,0128 | 1,0130 |
| 0,3000 | 0,09 | 0,9939 | 0,9982 | 1,0014 | 1,0060 | 1,0093 | 1,0128 | 1,0147 | 1,0163 | 1,0166 |
| 0,3162 | 0,10 | 0,9973 | 1,0015 | 1,0046 | 1,0092 | 1,0125 | 1,0162 | 1,0182 | 1,0199 | 1,0202 |
| 0,3317 | 0,11 | 1,0009 | 1,0050 | 1,0080 | 1,0126 | 1,0159 | 1,0196 | 1,0217 | 1,0235 | 1,0238 |
| 0,3464 | 0,12 | 1,0048 | 1,0086 | 1,0116 | 1,0160 | 1,0194 | 1,0230 | 1,0253 | 1,0272 | 1,0276 |
| 0,3606 | 0,13 | 1,0088 | 1,0123 | 1,0153 | 1,0197 | 1,0230 | 1,0266 | 1,0290 | 1,0309 | 1,0312 |
| 0,3742 | 0,14 | 1,0129 | 1,0163 | 1,0192 | 1,0235 | 1,0267 | 1,0303 | 1,0328 | 1,0347 | 1,0350 |
| 0,3873 | 0,15 | 1,0173 | 1,0206 | 1,0234 | 1,0274 | 1,0305 | 1,0341 | 1,0366 | 1,0385 | 1,0388 |
| 0,4000 | 0,16 | 1,0219 | 1,0251 | 1,0276 | 1,0316 | 1,0348 | 1,0380 | 1,0405 | 1,0424 | 1,0427 |
| 0,4123 | 0,17 | 1,0266 | 1,0297 | 1,0321 | 1,0358 | 1,0386 | 1,0420 | 1,0445 | 1,0463 | 1,0467 |
| 0,4243 | 0,18 | 1,0315 | 1,0344 | 1,0367 | 1,0402 | 1,0428 | 1,0461 | 1,0486 | 1,0504 | 1,0507 |
| 0,4359 | 0,19 | 1,0366 | 1,0393 | 1,0416 | 1,0447 | 1,0472 | 1,0503 | 1,0527 | 1,0545 | 1,0547 |
| 0,4472 | 0,20 | 1,0418 | 1,0444 | 1,0464 | 1,0494 | 1,0517 | 1,0546 | 1,0569 | 1,0586 | 1,0589 |
| 0,4583 | 0,21 | 1,0472 | 1,0496 | 1,0515 | 1,0543 | 1,0563 | 1,0590 | 1,0612 | 1,0628 | 1,0631 |
| 0,4690 | 0,22 | 1,0528 | 1,0550 | 1,0567 | 1,0593 | 1,0611 | 1,0636 | 1,0656 | 1,0671 | 1,0674 |
| 0,4796 | 0,23 | 1,0586 | 1,0606 | 1,0621 | 1,0644 | 1,0660 | 1,0682 | 1,0701 | 1,0715 | 1,0718 |
| 0,4899 | 0,24 | 1,0645 | 1,0662 | 1,0677 | 1,0697 | 1,0710 | 1,0730 | 1,0746 | 1,0760 | 1,0762 |
| 0,5000 | 0,25 | 1,0706 | 1,0721 | 1,0734 | 1,0751 | 1,0763 | 1,0779 | 1,0793 | 1,0805 | 1,0807 |
| 0,5099 | 0,26 | 1,0769 | 1,0782 | 1,0792 | 1,0806 | 1,0816 | 1,0830 | 1,0841 | 1,0852 | 1,0854 |
| 0,5196 | 0,27 | 1,0833 | 1,0844 | 1,0853 | 1,0864 | 1,0871 | 1,0881 | 1,0890 | 1,0899 | 1,0901 |
| 0,5292 | 0,28 | 1,0899 | 1,0908 | 1,0914 | 1,0923 | 1,0928 | 1,0934 | 1,0941 | 1,0948 | 1,0949 |
| 0,5385 | 0,29 | 1,0966 | 1,0972 | 1,0976 | 1,0982 | 1,0985 | 1,0989 | 1,0993 | 1,0995 | 1,0999 |
| 0,5477 | 0,30 | 1,1035 | 1,1037 | 1,1039 | 1,1042 | 1,1043 | 1,1045 | 1,1046 | 1,1049 | 1,1049 |
| 0,5568 | 0,31 | 1,1106 | 1,1106 | 1,1105 | 1,1104 | 1,1102 | 1,1101 | 1,1101 | 1,1101 | 1,1101 |
| 0,5657 | 0,32 | 1,1179 | 1,1176 | 1,1173 | 1,1168 | 1,1164 | 1,1159 | 1,1156 | 1,1155 | 1,1154 |
| 0,5745 | 0,33 | 1,1253 | 1,1246 | 1,1241 | 1,1233 | 1,1225 | 1,1218 | 1,1214 | 1,1209 | 1,1208 |
| 0,5831 | 0,34 | 1,1329 | 1,1320 | 1,1312 | 1,1300 | 1,1290 | 1,1279 | 1,1272 | 1,1266 | 1,1264 |
| 0,5916 | 0,35 | 1,1407 | 1,1394 | 1,1384 | 1,1368 | 1,1355 | 1,1341 | 1,1332 | 1,1324 | 1,1321 |
| 0,6000 | 0,36 | 1,1486 | 1,1470 | 1,1457 | 1,1438 | 1,1423 | 1,1406 | 1,1394 | 1,1383 | 1,1379 |
| 0,6083 | 0,37 | 1,1567 | 1,1548 | 1,1532 | 1,1510 | 1,1493 | 1,1472 | 1,1457 | 1,1445 | 1,1439 |
| 0,6164 | 0,38 | 1,1650 | 1,1627 | 1,1609 | 1,1583 | 1,1564 | 1,1540 | 1,1523 | 1,1508 | 1,1501 |
| 0,6245 | 0,39 | 1,1734 | 1,1709 | 1,1688 | 1,1658 | 1,1636 | 1,1609 | 1,1590 | 1,1573 | 1,1565 |
| 0,6325 | 0,40 | 1,1821 | 1,1793 | 1,1768 | 1,1735 | 1,1711 | 1,1680 | 1,1660 | 1,1641 | 1,1630 |
| 0,6403 | 0,41 | 1,1909 | 1,1877 | 1,1851 | 1,1813 | 1,1788 | 1,1754 | 1,1732 | 1,1710 | 1,1698 |

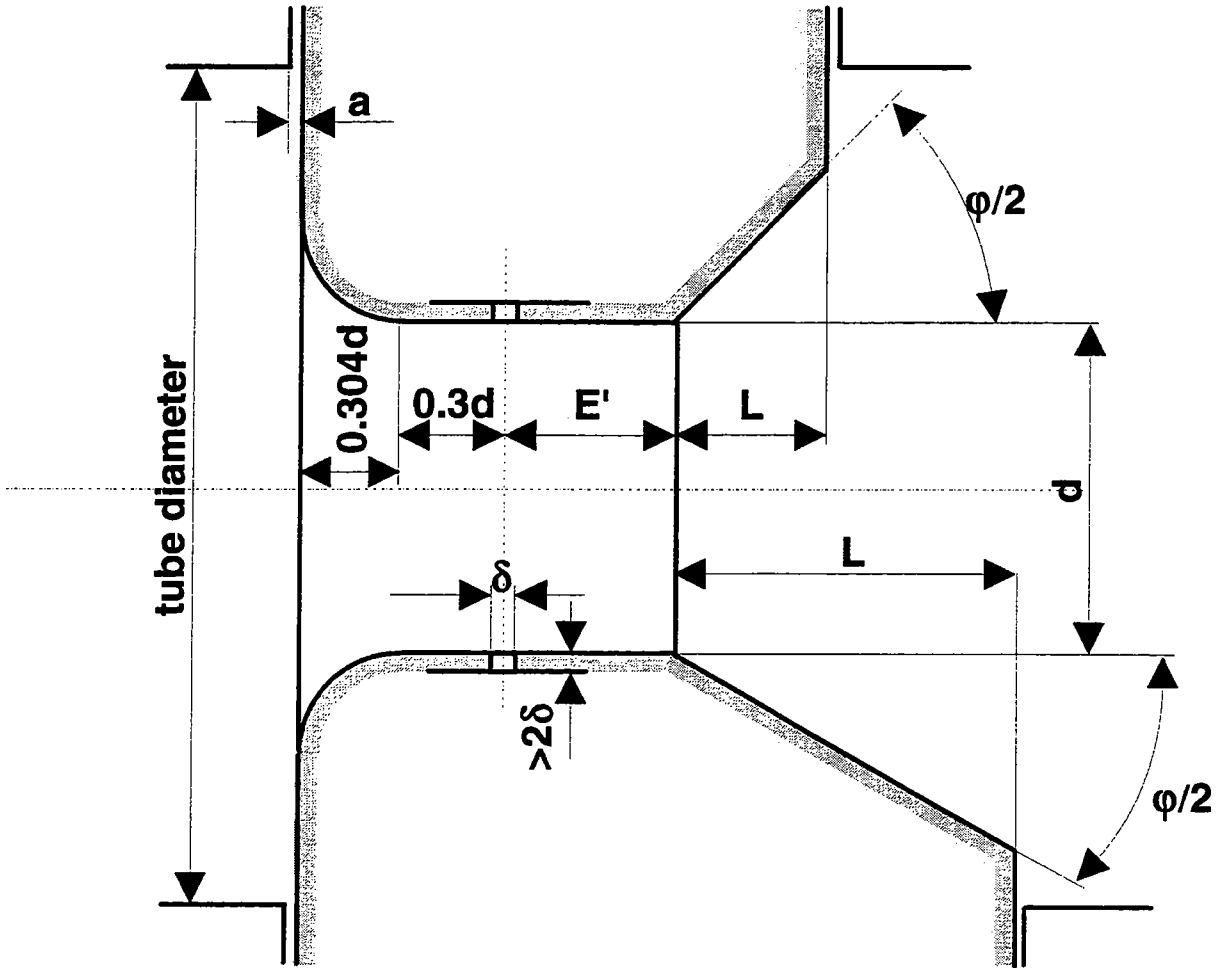
4.2 Standard Orifices and Venturi-Nozzles

Orifices and Venturi-nozzles are standardized in the same way as above-mentioned standard nozzles.

The following figure shows the two standard orifices distinguished only in the pressure taps.



The following figure shows the two used Venturi nozzles distinguished only in the length of the diffuser part.



5. CALCULATION OF DENSITY

5.1 Requests, Calculation of Real Conditions

The methods based on the law of Bernoulli needs the knowledge of the density ρ of gas. For simple gases like dry air this request makes normally no problem. In case of kiln gases e.g. the density must be evaluated or approximated to the real condition.

$$p_0 = 760[\text{Torr}] = 760[\text{mmHg}] = 1.01325 \cdot 10^5 \left[\frac{\text{N}}{\text{m}^2} \right] \text{ or } [\text{Pa}]$$

$$T_0 = 273.16[\text{°K}] = 0[\text{°C}]$$

$$1[\text{mmHg}] = 133.322 \left[\frac{\text{N}}{\text{m}^2} \right] \text{ or } [\text{Pa}]$$

In case of air and in function of the relative humidity ϕ is almost invariant:

Table 1

| ϕ [%] | ρ_0 [kg/m^3] |
|------------|------------------------------|
| 100 | 1.290 |
| 80 | 1.290 |
| 60 | 1.291 |

Thus, the actual gas density ρ_G can be found with the following correlation:

$$\rho_G = \rho_0 \frac{T_0 \cdot p_G}{T_G \cdot p_0} = 1.29 \frac{273.16 \cdot p_G}{T_G \cdot 1.01325 \cdot 10^5}$$

where p_G = actual static gas pressure [N/m^2]
 T_G = actual gas temperature [K]

p_G can be measured by adding the differential pressure between tube and the ambient to the barometric pressure.

5.2 Gas Compositions

Mainly in the field of kiln, the gas compositions can be very different so that their density must be determining. The greatest influences to the density come from the components carbondioxide (CO₂) and water content (H₂O, humidity). Often both components are unknown and can't be measured easily, so that the user depend from approximations.

5.2.1 Calculation of a Heterogeneous Gas

Density of dry gas composition: ρ_{ndr}

| Component | Content [%] | Factor | Part of | Unit |
|-----------------|-------------|----------------|---------|-----------------------------|
| CO ₂ | | 1.977 | | [kg/m ³ ,N, dr.] |
| O ₂ | | 1.429 | | [kg/m ³ ,N, dr.] |
| CO | | 1.25 | | [kg/m ³ ,N, dr.] |
| N ₂ | | 1.257 | | [kg/m ³ ,N, dr.] |
| | Σ 1.000 | $\rho_{ndr} =$ | | [kg/m ³ ,N, dr.] |

Density of wet gas composition:

$$\rho_{nw} = \frac{\rho_{ndr} + W_o}{1 + f_{dr}}$$

Where

| | | |
|------------|---------------------|--|
| $W_o =$ | Water content | [kg/m ³ n,dry] |
| $f_{dr} =$ | $\frac{W_o}{0.804}$ | [m ³ /m ³ n,dry] |

6. PRACTICAL WORK IN GAS FLOW MEASUREMENT

6.1 Test Equipment

The measurement of the velocity profile and the volume flow is shown on a special test equipment which is sketched in the following figure.

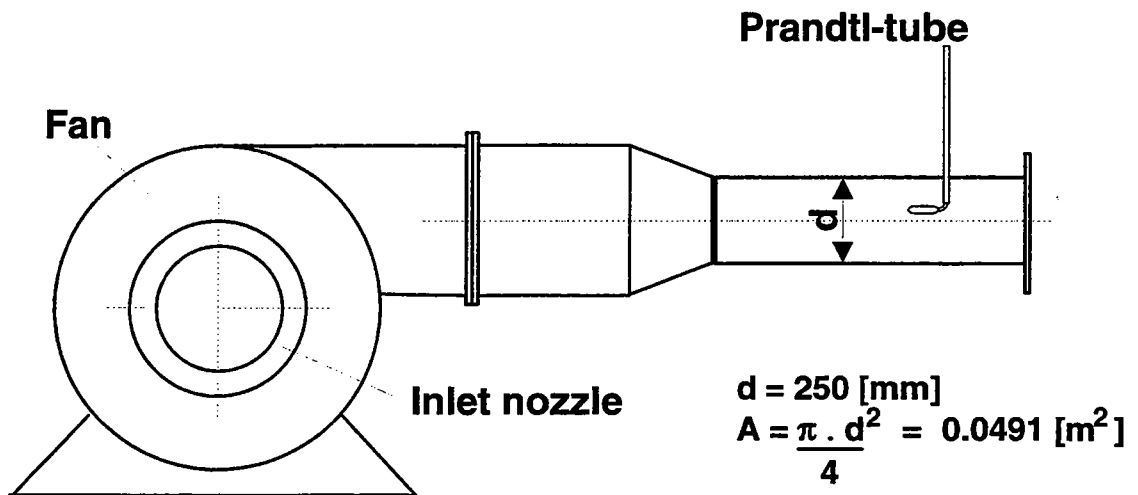


Fig. 1

The following measuring methods are demonstrated and applied:

- 1) **Prandtl Tube:** The velocity will be measured on several points of the cross sectional area by means of which the average velocity and the volume rate will be calculated.
- 2) **Anemometers:** At the outlet of the test equipment the mean velocity will be measured with two different anemometers.
- 3) **Fan Characteristics:** With the knowledge of the characteristic curves of the fan given by the supplier, the volume rate is determined by the pressure difference of the fan and the revolutions of the fan.
- 4) **Inlet Nozzle (Piezometer):** At the suction side of the fan an inlet nozzle is attached. This nozzle is calibrated and the volume rate can be calculated by means of the pressure difference between the nozzle inlet and ambient.

6.2 The Prandtl Tube

Prandtl tubes are mainly used for speed measurements of gaseous mediums. The application of a Prandtl tube is suitable for following measurements:

- ◆ Higher Temperatures (Until 500°C, depending of construction materials)
- ◆ Few dust loaded gas flows (approx. 50 g/m³ max.)
- ◆ Only for higher gas velocities (approx. 10 m/s min.)
- ◆ The density of the medium must be known

The Prandtl tube itself is a very simple and cheap measuring instrument. Because the measuring is selectively for an integral gas flow measurement several measuring points must be measured. Therefore, the time consumption for the measurement itself and the evaluation is considerable.

Most application in cement industry for Prandtl tubes are:

- ◆ Air output of grate coolers
- ◆ Riser ducts
- ◆ Tertiary air ducts
- ◆ etc.

Generally, the application of Prandtl tubes are indicated when other instruments e.g. anemometers as a result of high temperatures or other reasons cannot be used.

If a Prandtl tube is put into a flowing medium, the following pressures are produced:

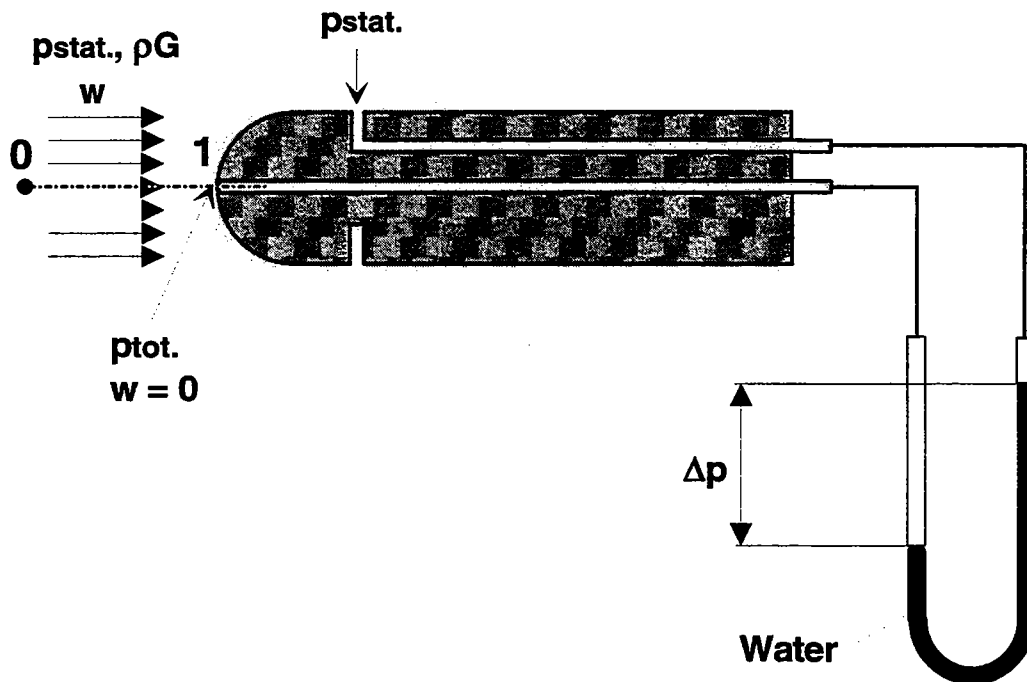


Fig.2

The total pressure P_{tot} acts on the ball-shaped measuring head, composed of the static pressure P_{stat} and the dynamic pressure. The Bernoulli-equation formulated from the point 0 (ambient point) to the point 1 (pressure point) states:

$$p_{stat} + \frac{\rho_G}{2} w^2 = p_{tot} \text{ total pressure} \quad (1)$$

\uparrow dynamic pressure
 \uparrow static pressure

The flow speed is only influenced by the dynamic pressure:

$$w = \sqrt{\frac{2}{\rho_G} (p_{tot} - p_{stat})} \quad (2)$$

Its value is obtained from the difference of the total pressure P_{tot} and the static pressure P_{stat} read on a differential pressure gauge.

$$(p_{tot} - p_{stat}) = \rho_G g h \quad (3)$$

From equation (2) and (3)

$$w = \sqrt{2g \frac{w}{\rho_G} h} \quad (4)$$

PS: Prandtl tubes are insensitive to deviations from the flow direction up to an angle of about $\pm 10^\circ$ only (See chapter 3, Fig 2)

6.2.1 Calculation of the Gas Density

Theoretically, the real gas density ρ_G , considering the humidity, should be calculated by determination of the water content or the dew point. The influence of the humidity is only relevant in case of high temperature and high water contents, e.g. exhaust gas of the kiln.

In the case at hand the density of moist air on standard conditions

$$p_0 = 760[\text{Torr}] = 760[\text{mmHg}] = 1.01325 \cdot 10^5 \left[\frac{\text{N}}{\text{m}^2} \right] \text{ or } [\text{Pa}]$$

$$T_0 = 273.16[^\circ\text{K}] = 0[^\circ\text{C}]$$

$$1[\text{mmHg}] = 133.322 \left[\frac{\text{N}}{\text{m}^2} \right] \text{ or } [\text{Pa}]$$

$$1[\text{mbar}] = 10^2 \left[\frac{\text{N}}{\text{m}^2} \right] \text{ or } [\text{Pa}]$$

and in function of the relative humidity ϕ is almost invariant:

Table 1

| ϕ [%] | ρ_0 [kg/m^3] |
|------------|-------------------------------------|
| 100 | 1.290 |
| 80 | 1.290 |
| 60 | 1.291 |

Thus, the actual gas density ρ_G can be found with the following correlation:

$$\rho_G = \rho_0 \frac{T_0 \cdot p_G}{T_G \cdot p_0} = 1.29 \frac{273.16 \cdot p_G}{T_G \cdot 1.01325 \cdot 10^5} \quad (5)$$

where

$p_G =$ actual static gas pressure [N/m^2]
 $T_G =$ actual gas temperature [$^\circ\text{K}$]

P_G can be measured by adding the differential pressure ΔP_s between the tube and the ambient to the barometric pressure.

6.2.2 Numerical Calculation of Density

| | | | |
|---------------------|-------|---|--|
| Barometric pressure | P_a | = | [mbar] |
| | | = | $\cdot 10^5$ [N/m ²] |
| Static pressure | P_s | = | [mmW]) |
| | | = | $\cdot 10^5$ [N/m ²] |
| Gas pressure | P_G | = | $p_a + P_s =$ $\cdot 10^5$ [N/m ²] |
| Gas temperature | t_G | = |[°C] |
| | T_G | = |+ 273 [°K] |

$$\rho_G = 1.29 \frac{273.16 \cdot p_G}{T_G \cdot 1.01325 \cdot 10^5}$$

$$\rho_G = 1.29 \frac{273.16 \cdot \dots \cdot 10^5}{\dots \cdot 1.01325 \cdot 10^5} = \dots \left[\frac{kg}{m^3} \right]$$

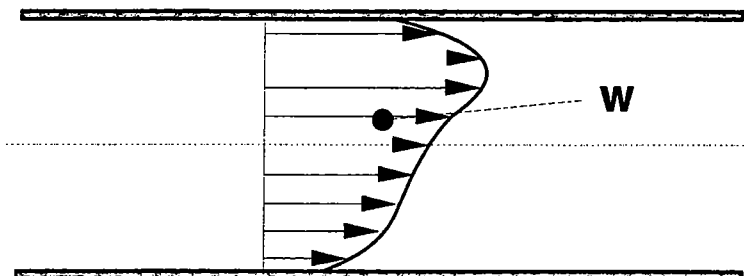
6.3 Calculation of the Gas Velocity

With the knowledge of the gas density ρ_G the gas velocity can be calculated by the following equation (6)

1000

.....

The velocity in the given tube is not constant over the cross section and a certain velocity profile appears:



For this reason the average velocity must be found. This is made by an integration of the local velocities over the cross sectional area.

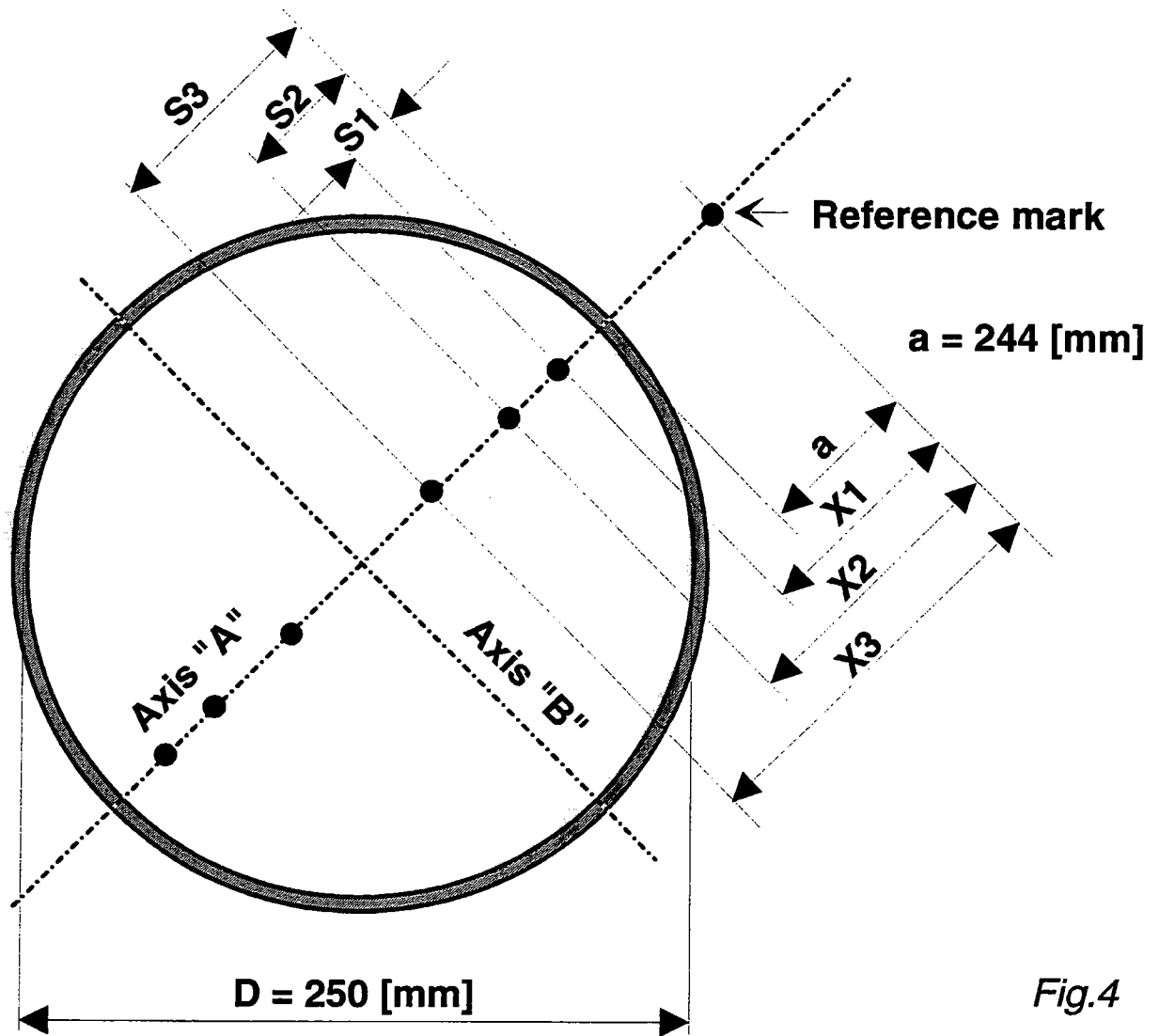
In order to split the integration in discrete values, the cross sectional area was shared in equal-sized concentric sections, each including four measuring points (two on each measuring axis). The locations where the pressure measurement are to be carried out depend on the desired total number of measuring points to be made on each measuring axis (see Table 2 and Figure 4).

Table 2

| | 12 measuring points | 10 measuring points | 8 measuring points | 6 measuring points |
|----|----------------------------|----------------------------|---------------------------|---------------------------|
| 1 | 0.022 x D | 0.025 x D | 0.032 x D | 0.043 x D |
| 2 | 0.067 x D | 0.080 x D | 0.105 x D | 0.146 x D |
| 3 | 0.118 x D | 0.145 x D | 0.194 x D | 0.296 x D |
| 4 | 0.177 x D | 0.225 x D | 0.323 x D | 0.704 x D |
| 5 | 0.250 x D | 0.340 x D | 0.677 x D | 0.853 x D |
| 6 | 0.356 x D | 0.660 x D | 0.806 x D | 0.957 x D |
| 7 | 0.644 x D | 0.775 x D | 0.895 x D | |
| 8 | 0.750 x D | 0.855 x D | 0.968 x D | |
| 9 | 0.823 x D | 0.920 x D | | |
| 10 | 0.882 x D | 0.975 x D | | |
| 11 | 0.933 x D | | | |
| 12 | 0.979 x D | | | |

(D = Diameter)

For this measurement six points are taken



Distance from inside wall

$$s_1 = 9.043 \cdot D = 11 \text{ mm}$$

$$s_2 = 0.146 \cdot D = 37 \text{ mm}$$

Distance from a reference mark

$$x_1 = S_1 + a = 235 \text{ mm}$$

$$x_2 = S_2 + a = 261 \text{ mm}$$

Table 3

| Axis | Point | Distance from inside wall [cm] | Distance from reference mark [cm] | Δh^* [mm W] | Δh [m W] | Velocity (see 6) $w = \dots \cdot \sqrt{h}$ [m/s] |
|------|-------|--------------------------------|-----------------------------------|-------------------------------|------------------|--|
| A | 1 | 1.1 | 23.5 | | | |
| A | 2 | 3.7 | 26.1 | | | |
| A | 3 | 7.4 | 29.8 | | | |
| A | 4 | 17.6 | 40.0 | | | |
| A | 5 | 21.3 | 43.7 | | | |
| A | 6 | 23.9 | 46.3 | | | |
| B | 1 | 1.1 | 23.5 | | | |
| B | 2 | 3.7 | 26.1 | | | |
| B | 3 | 7.4 | 29.8 | | | |
| B | 4 | 17.6 | 40.0 | | | |
| B | 5 | 21.3 | 43.7 | | | |
| B | 6 | 23.9 | 46.3 | | | |
| | | | | $\bar{w} = \frac{\sum w}{12}$ | | |

6.4 Calculation of the Gas Flow Rate

a) Operating conditions

$$\dot{V} = A_T \cdot \bar{w} = 0.0491 \cdot \dots = \dots \left[\frac{\text{m}^3}{\text{s}} \right]$$

b) Standard conditions

$$\dot{V}_0 = V_G \frac{\rho_G}{\rho_0} = \dots \frac{\dots}{1.29} = \dots \left[\frac{\text{Nm}^3}{\text{s}} \right]$$

6.5 Anemometers

6.5.1 Type A (Vane Wheel Anemometers)

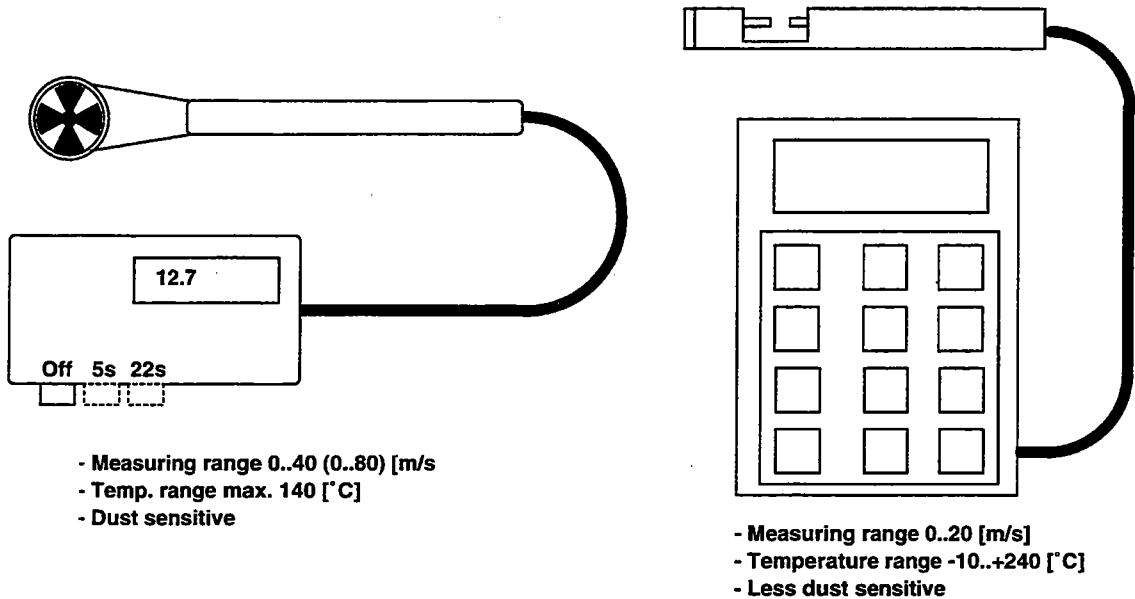


Fig.5

A: Vane wheel Anemometer

B: Thermal gasflow meter

The revolutions of the vane, being proportional to the gas velocity, have directly been measured by an electronic sensor. The instrument integrates the number of revolutions by a certain time and the indication is in meter per second:

$$w_A = \dots \dots \dots \left[\frac{m}{s} \right]$$

$$\bullet V = A_T \cdot w_A = 0.0491 \dots \dots \dots = \dots \dots \dots \left[\frac{m^3}{s} \right]$$

Vane wheel anemometers are independent of gas condition.

6.5.2 Type B Thermal Anemometers

Thermal gas flow meters were based on the principle of heat transfer from an electrical heated body to the ambient medium (gas) depending from the relative velocity between body and medium. The probe consists of a heated temperature sensor and two additional temperature sensors. The first sensor measures the temperature of the heated sensor and the second the temperature of the medium. The temperature difference between heated sensor and the medium contains the information for calculating the gas velocity with the aid of an integrated micro processor.

The indication of thermal gasflow anemometers is depending from gas conditions:

- ◆ specific heat
- ◆ conductivity
- ◆ density

The calibration is normally based on the medium air. For other gases (kiln gases) correction factors should be used. Tables with such factors are available from the suppliers.

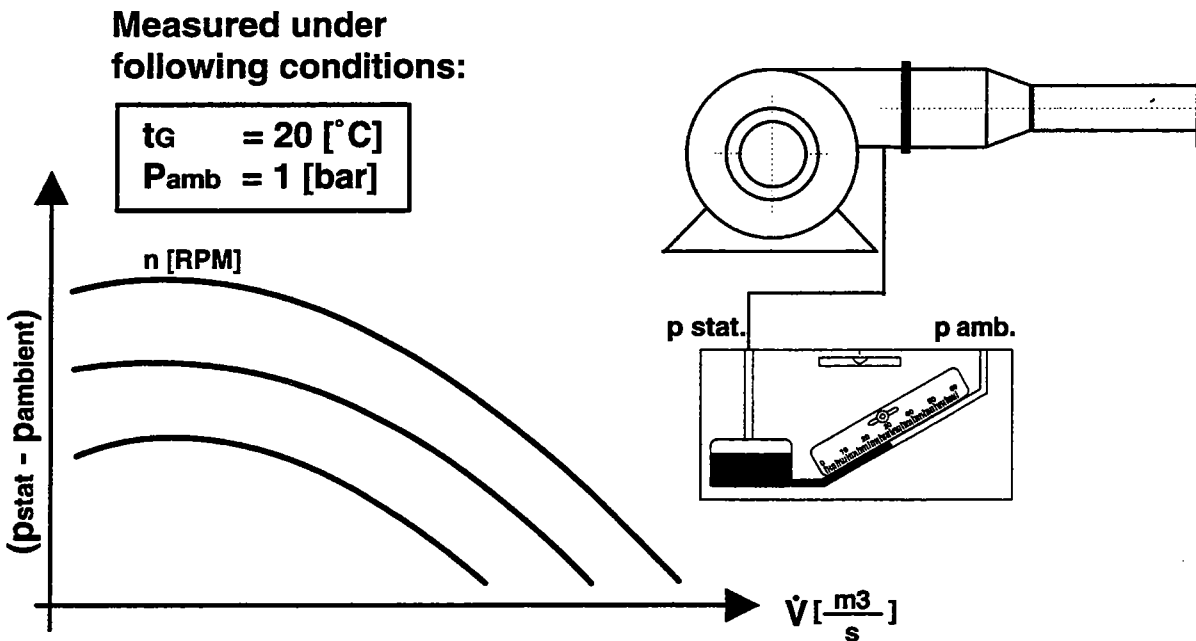
6.5.3 Vortex Anemometers (not used in practical work)

When a object is inserted in a flowing fluid then a vortex tail, known as Karman vortex street, arises. Karman found (about 1912) out, that depending on the velocity a constant relation exists between vortex interval and vortex sequence behind a cylindrical body in a current. He also observed that at constant flow velocity the vortex frequency downstream remains practically constant.

Vortex anemometers are independent of gas conditions like density, pressure and temperature until 180°C. Vortex measuring probes have no moving parts. They are robust, reliable and corrosion-resistant. Even in rough conditions as dust loaded fluids a high fatigue strength is ensured.

6.6 Characteristic Curves of the Fan

The supplier establishes the fan characteristics by measuring the difference between the static pressure at the fan outlet and the total pressure at the fan inlet in function of the revolutions of the fan and the volume rate. This measurement is given by the following diagram.



PS: For most fans in cement plants, it is satisfactory to assume that the fan's static pressure is the difference between the static pressure at the inlet (here atmospheric pressure) and outlet of the fans.

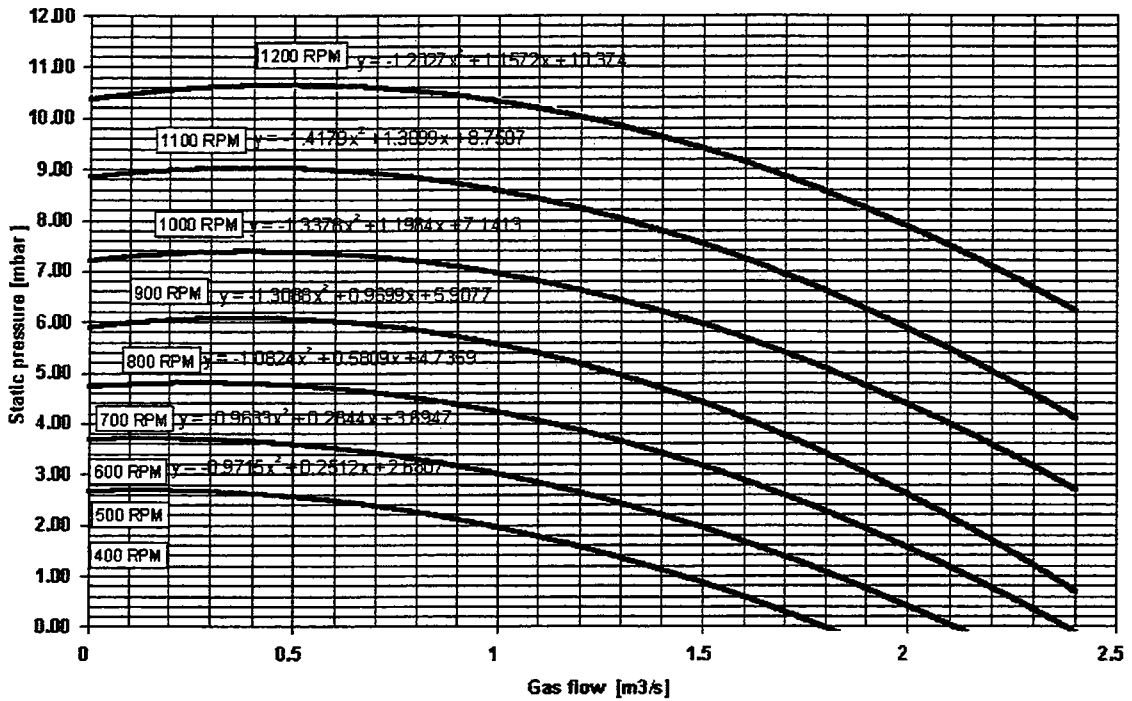
6.6.1 Measurements

$n = \dots\dots\dots$ [rpm]

$\Delta p = \dots\dots\dots$ [mbar]

From the given diagram by the supplier: $V_f = \dots\dots\dots$ [m³/s]

Test Fan Laboratory Hall



6.7 INLET NOZZLE

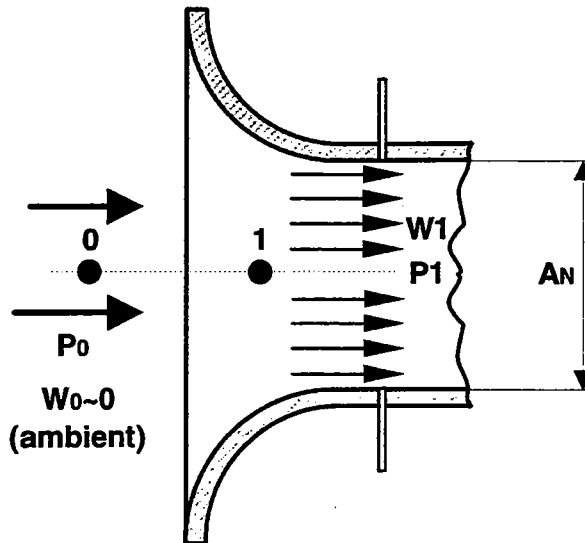


Fig. 8

Equation of Bernoulli:

$$w_0 = \frac{p_0}{\rho_G} + \frac{w_0^2}{2} = \frac{p_1}{\rho_G} + \frac{w_1^2}{2} \quad (7) \quad (8)$$

$$w_1 = \sqrt{\frac{2(p_0 - p_1)}{\rho_G}}$$

Continuity condition:

$$V_f = A_N \cdot w_1 = A_N \cdot \sqrt{\frac{2(p_0 - p_1)}{\rho_G}} \quad (9)$$

U - Tube manometer:

$$(p_0 - p_1) = \rho_w \cdot g \cdot \Delta h \quad (10)$$

From equations (9) and (10) :

$$V_f = \alpha \cdot A_N \cdot \sqrt{2g \frac{\rho_w}{\rho_G} \Delta h} \quad (11)$$

- $\alpha = 0.93$ [-] (measured by the supplier)
- $A_N = 0.1244$ [m²]
- $\rho_w = 1000$ [kg/m³]
- $\rho_G = \dots\dots\dots$ [kg/m³] (see 2.2)
- $\Delta h = \dots\dots\dots$ [mm W] · 0.001 [m WC]
- $V_f = 0.93 \cdot 0.1244 \cdot \sqrt{29.81 \frac{1000}{\dots\dots\dots}}$
- $V_f = \dots\dots\dots$ [m³/s]

6.8 Manometers

6.8.1 Inclined Stationary Manometer

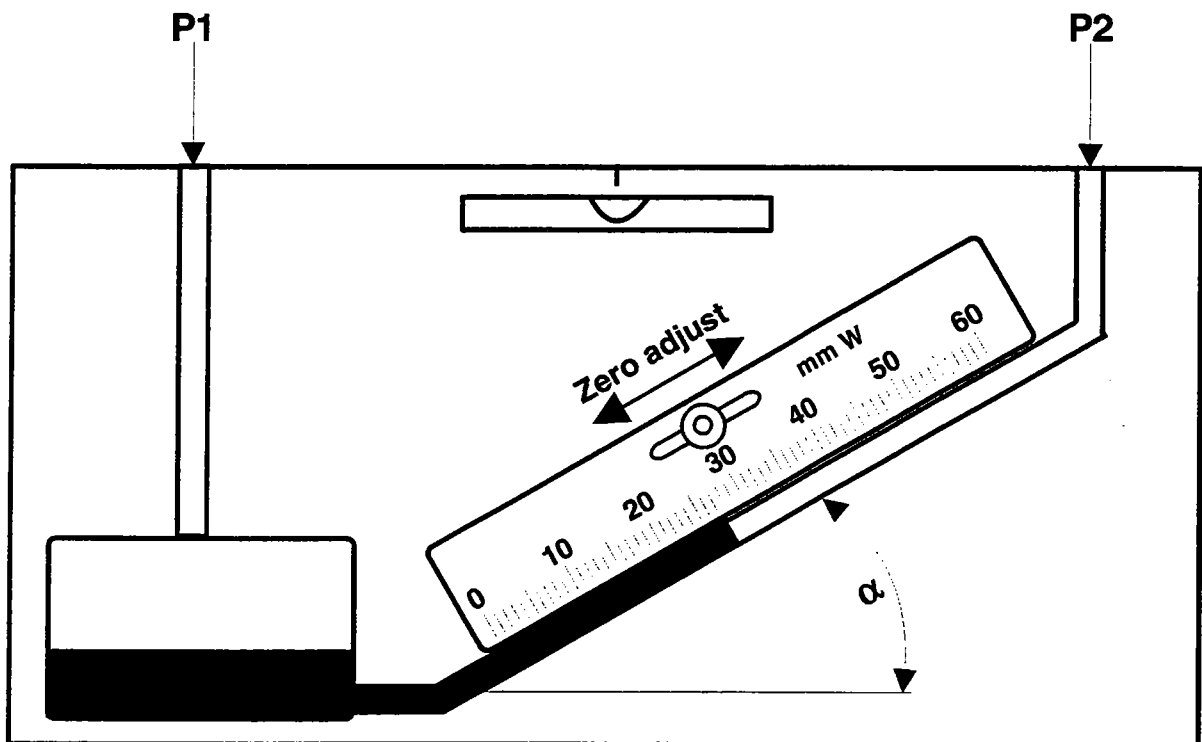


Fig. 9

PS: On the instrument itself mostly not the angle α is indicated but directly the value of $\sin \alpha$, e.g.

$$1 : 5 = 0.2 = 11.5^\circ$$

$$1 : 2 = 0.5 = 30.0^\circ$$

The angle of the used manometer is fixed and the scale is calibrated in mm W

7. SYMBOL LIST OF GAS FLOW MEASUREMENT

| | | |
|-----------------|--------------------------------------|--|
| A | [m ²] | Cross section area |
| d | [m] | Diameter of the smallest aperture |
| D | [m] | Diameter of the tube |
| h | [m] | Height of Liquidcolumn |
| m | [-] | Cross section area ratio $m = d^2 / D^2$ |
| \dot{m} | [kg / s] | Mass flow rate |
| p | [N / m ²] | Pressure |
| \dot{V} | [m ³ / s] | Volume flow rate |
| w | [m / s] | Velocity |
| α | [-] | Correction factor for the contraction |
| φ | [%] | Humidity |
| ϵ | [-] | Correction factor if fluid is compressible |
| ρ | [kg / m ³] | Density |
| f _{dr} | [m ³ /m ³ dry] | Water content (Volume) |
| W ₀ | [kg/m ³ n,dry] | Water content (Mass) |